Embedded Linux Conference
North America

- Tracing resource-constrained embedded systems using eBPF

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Agenda

- About me
- Embedded / IoT woes
- How does eBPF fit in?
- Quick eBPF / BCC introduction, benefits
- Approaches to eBPF on embedded devices
- Trade-offs, specific projects pros/cons
- Ways forwards

About me.

I enjoy

working in a company of awesome FOSS-oriented people at Collabora

work with companies who “get it” when using FOSS

work to help companies “get it” and be successful

I also really enjoy

Taking systems apart and modifying them

Projects like OpenEmbedded/Yocto, Buildroot/OpenWRT

Always looking for new tech to improve development and debugging of embedded devices

Learning about eBPF (just a user, not an expert)

A strong dislike of locked-down devices /
that lock owner usage without very good reasons

Embedded and the IoT

- “Smart” devices everywhere
- Increasingly powerful, complex, connected hardware
- Much more capable than default software installations allow
- Software complexity is also rising

    (embedded systems now programmed in JavaScript)
- Obvious privacy, security and vendor lock-in concerns

Embedded problems

Devices have more power and run modern software

yet they are really hard to

develop, debug, maintain and extend

Embedded problems

Why?

Embedded problems

Why?

Increased SW/HW complexity

+

Embedded-specific **resource constraints**

Resource constraints

- Enough memory to run just a specific pre-built workload
- Cross-compiling and flashing/provisioning
- Special “Embedded Linux” distributions
- RT deadline requirements
- Ergonomics trade-offs, lack of HW ports
- Licensing requirements (no GPLv3...)
- Weird HW combinations, countless HW revisions
- Throw-away HW, planned obsolescence
- Low quality Out-Of-Tree drivers
- <Add your own pet-peeve here>

Creative solutions against constraints

- Debug symbol servers and remote GDB sessions
- Booting rootfs over the network
- Special protocols for diagnostics/log/trace
- Debug vs Release images, “developer mode”
- And so on

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Here comes eBPF

Wait a minute

Embedded-eBPF sounds like a solution in search of a problem...

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It kind of is.

“Embedded” engineers drooling over tools of “Cloud” engineers

Would like to have same system observability powers

Precedent: SMP on embedded

Explaining eBPF / BCC in a few slides!

BCC automates

VM bytecode

Kernel ↥ Userspace

Links at the end for better learning resources.

VM running bytecode in the Linux kernel

Bytecode loaded from userspace via bpf() syscall

Verified for safety, unsafe => syscall rejects bytecode

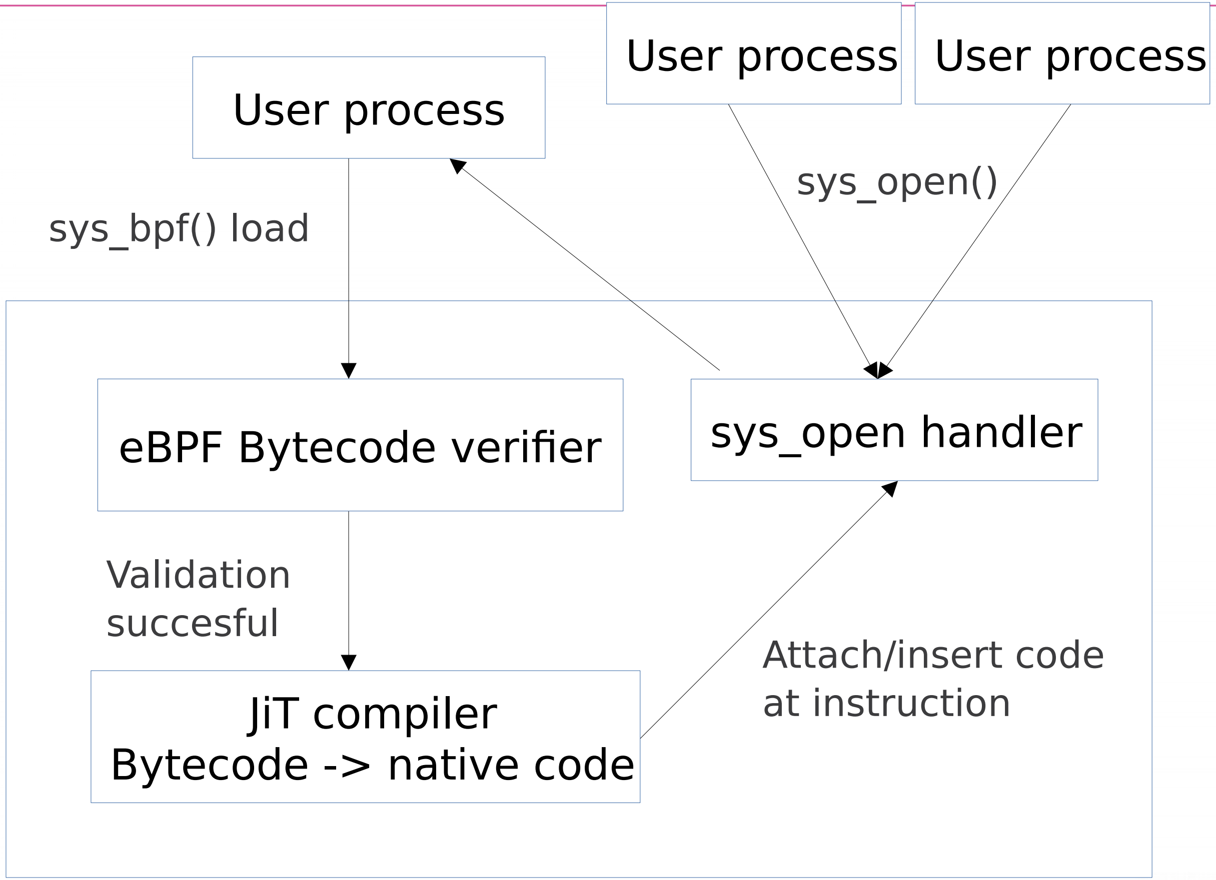
Bytecode compiled to native machine code

Native code inserted in execution paths

Event-driven programming

Native code runs and collects data

Data shared with userspace



User process
User process
User process
sys_open()
sys_bpf() load
eBPF Bytecode verifier
sys_open handler
Validation
succesful
Attach/insert code
at instruction
JiT compiler
Bytecode -> native code

How does userspace produce that bytecode?

```
0:  79 12 60 00 00 00 00 00    r2 = *(u64 *)(r1 + 96)
1:  7b 2a 98 ff 00 00 00 00    *(u64 *)(r10 - 104) = r2
2:  79 17 70 00 00 00 00 00    r7 = *(u64 *)(r1 + 112)
3:  85 00 00 00 0e 00 00 00    call 14
4:  bf 06 00 00 00 00 00 00    r6 = r0
5:  b7 09 00 00 00 00 00 00    r9 = 0
6:  7b 9a c0 ff 00 00 00 00    *(u64 *)(r10 - 64) = r9
7:  bf 73 00 00 00 00 00 00    r3 = r7
8:  07 03 00 00 18 00 00 00    r3 += 24
9:  bf a1 00 00 00 00 00 00    r1 = r10
11: 07 01 00 00 c0 ff ff ff    r1 += -64
12: b7 02 00 00 08 00 00 00    r2 = 8
13: 85 00 00 00 04 00 00 00    call 4
```

How does userspace produce that bytecode?

Directly write it byte by byte! 😱

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Clang can translate “restricted C” into eBPF bytecode

Much easier than assembling bytes like the 1960s

Still hard to write userspace interaction

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BCC: the **B**PF **C**ompiler **C**olection

- Framework to ease writing userspace eBPF programs
- Abstracts Clang and sys_bpf() interaction
- “restricted C” compiled & loaded in kernel on-the-fly
- Provides Python, Lua and Go bindings
- Provides production ready BCC-tools

BCC program

```
#!/usr/bin/env python
from bcc import BPF

csrc = """
#include <uapi/linux/ptrace.h>

int kprobe__do_sys_open(struct pt_regs *ctx)
{
        char file_name[256];
        bpf_probe_read(&file_name, sizeof(file_name), PT_REGS_PARM1(ctx));
        bpf_trace_printk(fmt, sizeof(fmt), file_name);
}
"""

b = BPF(text=csrc)
b.attach_kprobe(event="do_sys_open", fn_name="kprobe__do_sys_open")
while True:
    time.sleep(1)
```

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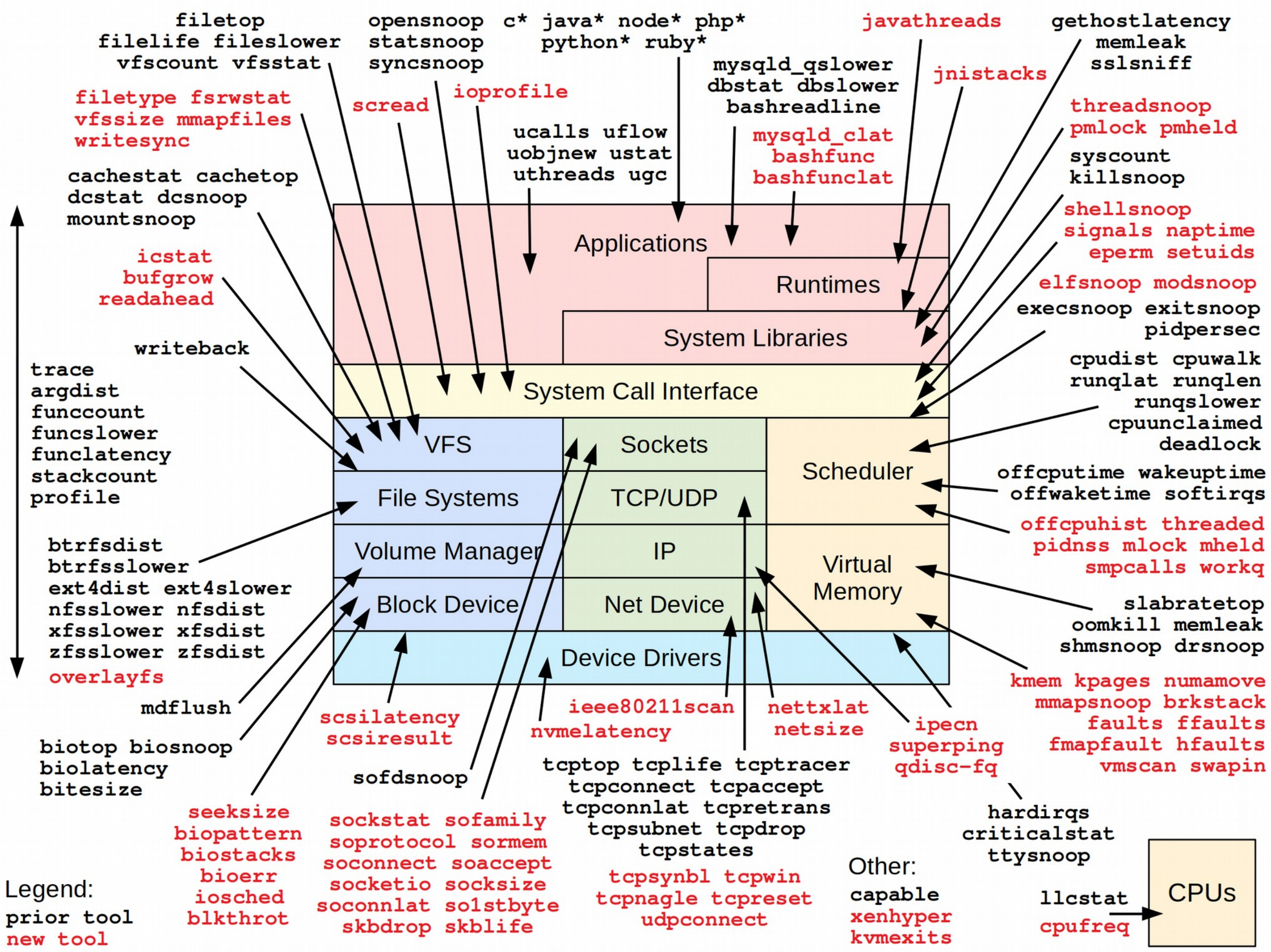
Compiled to bytecode
Loaded & runs in kernel
Collects data
Sends to userspace

Calls Clang to compile above code
Loads bytecode via bpf()

New tools developed for the book **BPF Performance Tools: Linux System and Application Observability** by Brendan Gregg (Addison Wesley, 2019), which also covers **prior BPF tools**



Real power comes with the **BCC tools**

Executive summary eBPF benefits

- System-wide observability
- No crashes / hangs
- No performance degradations
- Real-time production workload analysis
- Can be always enabled (no special debug builds) *
- Fully upstream kernel feature, active community
- Big collection of production-ready tools
- More than just observing a system

Packet filtering, hw offloading

Executive summary eBPF benefits

Convincing, yes?

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eBPF meets embedded

general / embedded-specific problems

multiple approaches

project advantages / disadvantages

trade-offs, no silver bullet

General problem: portability / cross-compilation

Poking “outside” from within the eBPF VM

- VM has generic 64 bit instructions/registers/pointers
- Difficulty accessing 32 bit kernel/user data structures
- VM is capable of 32 bit register subaddressing
- Pointer arithmetic hacks can access 32bit offset data

  Very fragile, not portable

- Better solution: **B**PF **T**ype **F**ormat adds type info to compiled eBPF

  (part of **C.O.R.E.**)

General problem: portability / cross-compilation

Portable eBPF (**C**ompile **O**nce, **R**un **E**verywhere)

- Dream: run precompiled eBPF an any machine and expect it to work
- Slimmer version of BCC using BTF info, no Clang runtime compilation
  (structure offsets built in BTF sections, macro identifiers → BPF variables)
- Current runtime compilation uses version/config specific C headers
  - Backwards, not forwards compatible
  - Manually copying non-UAPI structures to “restricted C”
  - Big variation of Linux kernel configs → *header* structures
- Kernel >= 5.2 can remove header filesystem dependency (kinda unrelated)
- Work on-going

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General problem: Security and unpriviledged eBPF

Running eBPF programs requires root / CAP_SYS_ADMIN

- eBPF code is assumed not malicious
- CAP_BPF will be added to restrict attack surface
- Unpriviliged eBPF unlikely to happen

Care must be taken when running eBPF code in production

- Don’t run arbitrary eBPF supplied by untrusted users
- Use additional security mechanisms like verified boot

Awesome (as always) relevant LWN.net article and comments:

https://lwn.net/Articles/796328/

Approach 1: Precompiled eBPF + custom userspace

PRO:
Lightest footprint possible
(few kb C program)

Kernel provides helper libbpf
(useful starting point)

CON:
Need to write from scartch
Userspace sys_bpf() interaction

Can get complex, hard to maintain
No pre-existing community

Some examples provided by Linux kernel tree
in samples/bpf/

Approach 2: Use BCC directly

PRO:
Vanilla upstream BCC
Full framework capabilities
All BCC-tools available
Well tested, good performance

CON:
Installs and links against Clang
Depends on Python (bcc-tools)
~ 300 MB storage

Will benefit from C.O.R.E., but will still require python

Example project: Androdeb
(Requires > 2GB storage)

Approach 3: BPFd

```
+---------------------------------+    SSH, Telnet     +------------------------------+
| Restricted C -> Python -> BCC <-=-------------------=-> BPFd <-> libbpf <-> kernel |
|                            |    |                    +------------------------------+
|   device kernel source -> LLVM  |                                   Embedded device
+---------------------------------+
                  Host machine
```

Project abandoned due to high maintenance cost

PRO:
100 kb bin + libc dependency
Full framework capabilities
All BCC-tools available

CON:
Hard to maintain BCC<>BPFd interaction
Host + target + transport
dependent architecture

Approach 4: DSL compiler from scratch - Ply

```
+-----------------------------------+    ssh/nfs/http    +----------------------------+
|            ply source -+--> GCC -=---------------------=-> ply compiler <-> kernel |
|                        |          |                    |    |                      |
| device kernel source -+           |                    |  script                   |
+-----------------------------------+                    +----------------------------+
               Developer machine                                   Embedded device
```

```
ply 'kprobe:i2c_transfer { print(stack); }'
```

PRO:
50 kb bin + libc dependency
High level, AWK-inspired DSL
Self-contained
Easy to build & deploy

CON:
Lack of kernel/user interaction control
Lack of BCC-tools diversity
Under heavy development
Ply binary is not portable

Approach 5: Replace BCC Python userspace with Go

PRO:

~2 mb static-compiled eBPF loader

Full control over kernel/user interaction

Good coverage of BCC API bindings

CON:

BCC-tools need rewriting in Go :)

Not much documentation

```
+-----------------------------------+   ssh/nfs/http   +-----------------------------+
|          Restricted C -+--> LLVM -=------------------=-> eBPF_ELF.o               |
|                        |          |                   |      |                      |
| device kernel source -+          |                   |      | loaded in kernel     |
|                                  |                   |      |                      |
|            Go source -> go build -=------------------=-> go_loader.bin <-> kernel |
+-----------------------------------+                  +-----------------------------+
                    Developer machine                                  Embedded device
```

Full execsnoop reimplementation:

https://github.com/iovisor/gobpf/blob/master/examples/bcc/execsnoop/execsnoop.go

Ways forward

- C.O.R.E. needs to be as succesful as possible
- With C.O.R.E. BCC will be more lightweight
- Gobpf can eliminate the Python dependency
- BPFd reached a dead end
- Ply is standalone, will continue its awesomeness
- eBPF on embedded is already useful today<
- Much work remaining

Recommended learning resources:

- LWN.net eBPF articles https://lwn.net/
- Brendan Gregg’s blog: http://www.brendangregg.com/blog/
- BPF Performance Tools: Linux System and Application Observability, by Brendan Gregg, published by Addison Wesley (2019)
- Collabora eBPF blog posts

  https://www.collabora.com/news-and-blog/blog/2019/04/05/an-ebpf-overview-part-1-introduction/
- Internet Search has wealth of information on eBPF

Thank you!

Psst...
We're hiring!

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